UHV Thin Film Sputter Deposition System

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Introduction

Thin-film deposition is any technique for depositing a thin film of material onto a substrate. It is useful in manufacturing optics, electronics (semiconductors), coatings (such as wear or corrosion resistance), and various composite materials. Thin film creation can be accomplished using a variety of different methods. The vast majority of these methods can be categorized into two regimes: chemical vapor deposition and physical vapor deposition. A substrate is exposed to various volatile precursor gases that react or decompose onto the substrate during chemical vapor deposition. On the other hand, physical deposition methods work by sputtering or evaporating the material, creating a gaseous plume that deposits a film onto the substrate.

Within an evaporative mechanism, the source material is heated until it evaporates and condenses on the substrate. Evaporation must occur in a vacuum, so that the mean free path will be large enough that the particles can travel directly to the substrate without colliding with the background gas molecules. Thermal methods to promote evaporation include radiative heating, resistive heating, electron-beam heating, and pulse-laser systems of suitable sources ("Thin Film Deposition Technical Notes," 2007).

I aided in the closing of a ultra-high vacuum (UHV) sputter deposition system, which is a method of coating a substrate using material that is removed from a solid target by energetic ion bombardment. This process needs to be done in UHV in order to prevent contaminants and to allow sputtered particles to travel far enough to be deposited onto the substrate. We therefore used a collection of vacuum gauges to measure the vacuum level within the chamber, as well as

various types of vacuum pumps to achieve the desired pressure. We also baked out the system by increasing the temperature of the actual stainless steel deposition chamber so the out-gassing speed inside the chamber would increase. Out-gassing molecules were then pumped out of the chamber so that few molecules would remain adsorbed to the inner surface. Therefore, once temperatures were lowered to ambient levels, the out-gassing rate would be low enough not to interfere with the vacuum level achievable in the chamber. Also, in order to maintain or create a vacuum, it was necessary to have a system of seals and valves to prevent outside contamination while still allowing the sample to be manipulated, sputter-gas inlet, or new components to be added to the system. Finally, we also needed a system of traps and filters to protect the system from contamination from foreign particles.

Once a clean vacuum has been achieved, sputter deposition can be carried out. This process bombards a target with low-eV ions so that atoms in the material are ejected due to collisions. In the present system a plasma was generated using ultra-high purity (99.999%) Argon gas and a high voltage source. The substrate positioning was also crucial since particles are ejected along line of sight yielding uniform films.

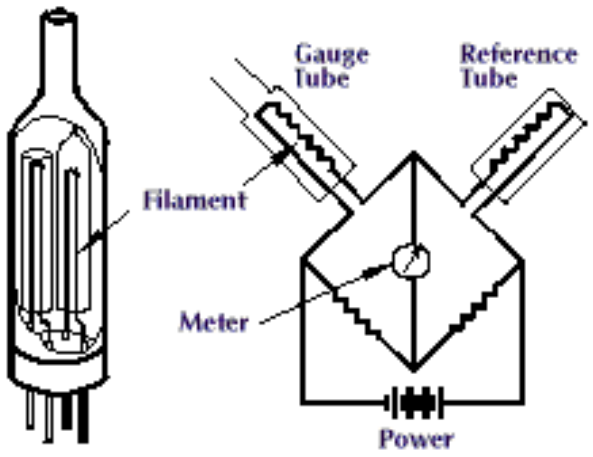
Vacuum Gauges

It is important to have an accurate method of measuring the pressure of gas within the chamber to carry out thin films deposition. Alas, there is no gauge capable of measuring pressure over the entire range of interest. Instead, we must select gauges for use within the pressure region of interest. For our purposes, we use thermal conductivity gauges to measure pressure above 10^{-3} Torr. We can gather the pressure by measuring the temperature of the filament inside the tube because the thermal conductivity of a gas is pressure-dependent in the

region below 2 Torr. As gas molecules collide with the filament, energy is dispersed, thereby cooling the filament at a rate based on the pressure of the gas. In order to measure the temperature, we can either use a thermocouple device that measures the temperature of the filament directly, or a Pirani gauge that measures the resistance of the filament. A thermocouple works by measuring the temperature difference between two points because of the thermoelectric effect (in which a thermal gradient creates a voltage) after a conductor made of a different metal is connected to the hot end and generates another voltage. The difference in voltages will be dependent then on the temperature difference between the hot and cold junctions of the filament ("Thermocouple," 2008).

On the other hand, a Pirani gauge operates by directly measuring the resistance of the filament. Usually one leg of a Wheatstone bridge circuit is connected to a reference tube at low pressure, while the filament of the other leg is left open to the air in the Pirani gauge. A schematic for a Pirani gauge is shown below in Figure 1. There is a limitation on the use of thermal conductivity gauges below 10^{-3} Torr, because in this range heat conduction through the supports of the gauge or radiative conduction through the vacuum will become dominant means of heat transfer, destroying the linear relationship between temperature and resistance (Berry, Hall, and Harris, 1968).

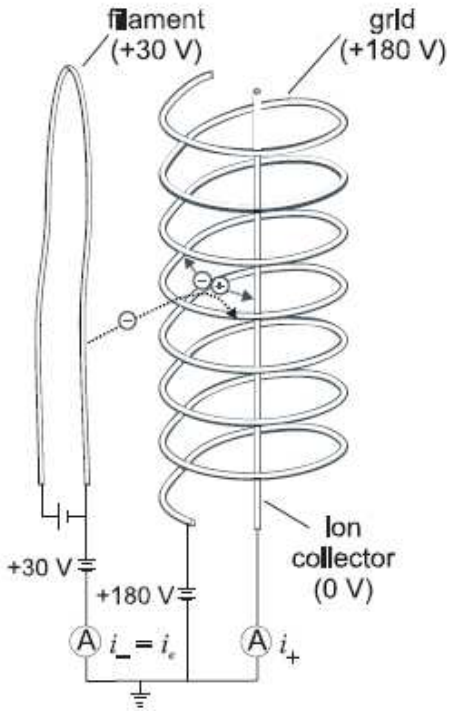
Figure 1: The Pirani gauge operates by measuring the resistance of a filament connected to the system in relation to the resistance of a reference tube.



Between 10^{-2} and 10^{-9} Torr, we typically rely on ion gauges for more accurate pressure measurements. Currently, two types of ion gauges are available within this pressure range. In the hot cathode design (which consists mostly of Bayard-Alpert models), ionizing electrons are emitted from a thermionic filament and accelerated by electrodes into an ionizing space. In contrast, a cold cathode design works by measuring ionization created by a circulating electron plasma moving through crossed electric and magnetic fields.

A Bayard-Alpert gauge boils electrons off of a filament, and accelerates them through a potential to a grid cage (as shown in Figure 2). When the electrons ionize the gases in the gauge, a wire inside the grid cage acts as an ion collector and absorbs the gas cations created. These cations then produce a current that is proportional to the density of the gas. As long as constant temperature is maintained, this effect is roughly linear. Bayard-Alpert gauges are gas dependent due to various ionization frequencies, and are usually calibrated for nitrogen or argon gas.

Figure 2: The Bayard-alpert gauge works by ionization gas molecules and then collecting the ions and measuring the current produced.

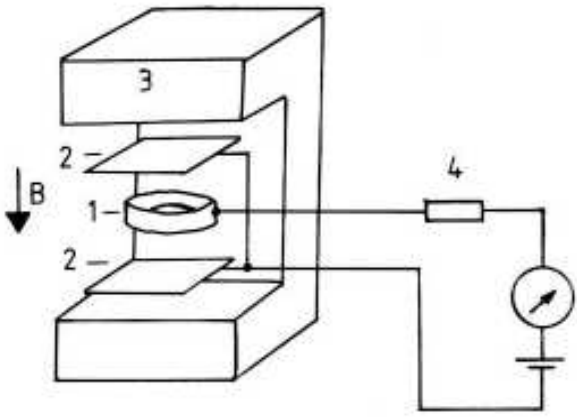


Limiting factors on the reliability of hot cathode gauges (HCGs) include possible thermal degassing of the filament, electron stimulated desorption of molecules in the metal, as well as interference caused by the photoelectric effect within the x-ray region. The x-rays create a residual collector current comparable to the ion signal of gases at 10^{-10} Torr. The first two effects cause out-gassing; however, this can be minimized by degassing the gauge, usually by passing a current through the grid and cleaning it by radiative heating. The final effect can also be minimized through the use of nude cage designs that have reduced collector and grid diameter sizes and closed ends to the grid. By doing this, pressure measurements in the 10^{-11} Torr range become more feasible ("Hot vs. Cold Ionization Gauges," 2005).

The major limitation of hot cathode designs is filament lifetime. This limits using the HCGs in higher pressures, where exposure to high pressure may damage the filament. Also, in this upper region the current to pressure relationship is no longer linear limiting the usefulness of the gauge. Because of the issue of filament lifetime, many people instead turn to cold cathode gauges for measurement.

A cold cathode gauge (CCG) creates a plasma waiting for the random release of an electron at the cathode or other random field emissions. A discharge slowly builds within the plasma, thereby limiting the entry of new electrons into the plasma. This discharge (at pressures below 10^{-4} Torr), creates a pure electron plasma discharge that moves in cycloidal jumps around the anode, ionizing the air. This probability of ionization is again proportional to gas density, thereby allowing current to be measured using an ion collector in the same way as in a HCG. Another limitation on the upper end of this type of gauge is the mean free path of the ions. If the mean free path is too small, then the ions will probably recombine before they get to the anode, limiting the accuracy of the reading. Because of this, the practical upper limit for a Penning type cold cathode gauge (see Figure 3) is 10^{-3} Torr. Pirani gauges are often coupled together with CCGs in a combined gauge to deal with the long start time and limited range they possess.

Figure 3: A Penning gauge creates a plasma that is manipulated using a magnetic field to ionize gas molecules and measure an ionization current.



Penning gauge diagram.
1. Anode, V=2-10kV
2. Cathode (grounded)
3. Permanent magnet (0.1-0.2 T)
4. Bleeder resistor

Cold cathode gauges have an exponential relationship between current and pressure, as opposed to the linear relationship in HCGs. Also, spurious discontinuities in the relationship limit accurate readings below 10^{-9} Torr. CCGs generally are considered less accurate than HCGs, but tend to take less time to come to stable readings. Moreover, CCGs typically possess lower out-gassing rates. While their long start time can be a problem, in operations requiring frequent pump-downs to low pressures without degassing, the CCG's readings tend to be more accurate than that of a HCG ("Hot vs. Cold Ionization Gauges," 2005).

Vacuum Pumps

In the process of creating a vacuum, the engineer is faced with the problem of limited ranges over which a pump can work efficiently. Because of this, pumps are classified as either working in the viscous flow region (also called fore-pumps or roughing-pumps) or the molecular flow region (known as high-vacuum pumps). Vacuum regions are also classified into rough vacuum (> 10^{-3} Torr), high vacuum (10^{-4} – 10^{-8} Torr), and ultra-high vacuum (10^{-9} – 10^{-12} Torr).

For the purpose of working in the viscous flow region, a mechanical pump of some design is often used. Two examples of this type of pump are the rotary vane pump, seen in Figure 4, and the roots blower pump, seen in Figure 5. These two pump types tend to operate in the region from atmosphere to 10^{-3} Torr.

Figure 4: Rotary vane pump operating by increasing the volume on the intake side of the pump to take in fluid which is then compressed out the exhaust.

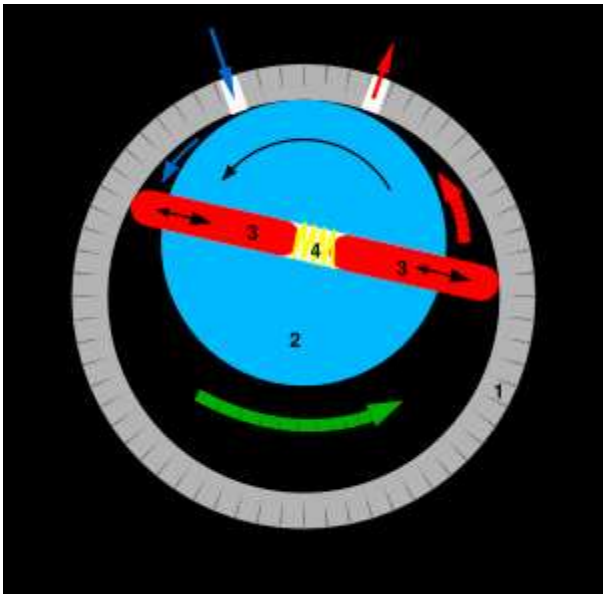
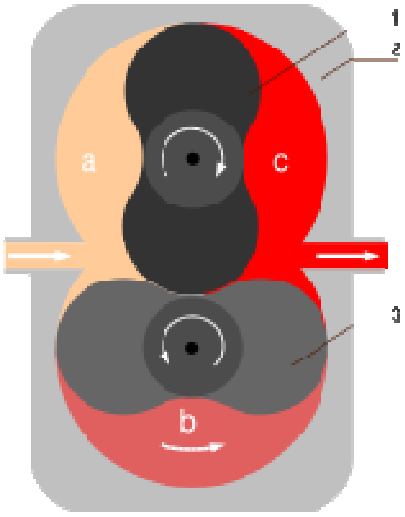


Figure 5: Roots blower pump that operates by using two spinning lobes to force air through the pump.



The rotary vane pump compresses the gas as the rotor (rotating component of pump) advances; meanwhile, oil is used to seal the sliding surfaces and minimize the clearance volume, thereby creating maximum compression. The ultimate pressure, or lowest achievable pressure, is limited by real and virtual gas leakage, as well as the vapor pressure of the oil. Real gas leakage is caused by poor seals, inlet connections, or by allowing gas to at some point cross from the exhaust to the inlet during compression through bypassing the rotor. Virtual gas leakage is caused either by contaminants in the oil or by out-gassing from the inlet material. Out-gassing is the slow release of gas that was absorbed or adsorbed to a material. On the other hand, air may dissolve in the oil and be delivered to the high vacuum region with the oil (Holkeboer, Jones, Pagano, and Santeler, 1967). As the compression ratio (ratio of volume of air in chamber before and after the compression stroke), rises to the point where the partial pressure of the water vapor is equal to its saturation value, the vapor begins to condense. This liquid may then contaminate the oil and pump, thus limiting the vapor pressure of water in the chamber. This effect can be

limited by the use of ballast gas (stabilizing gas) that is inserted into the pump before the compression stage to reduce the compression ratio. The detriment of gas ballast is that the ultimate pressure rises by a factor of ~10; however, usually the water vapor is reducing ultimate pressure by more than that. Finally, other contaminants can also have a limiting effect on the ultimate pressure by causing corrosion or blockage (Berry, Hall, and Harris, 1968).

Another type of common fore-pump is the roots blower pump. Roots blower pumps operate by two spinning lobes that are machined and aligned such that they are always within a few thousands of an inch of each other but never touch. Obviously, even though lubrication is unnecessary, gas leakage through the slight gap between the two lubes imposes a limitation on the compression ratio and ultimate pressure of this pump (Berry, Hall, and Harris, 1968). Operating roots pumps at full speed in atmosphere leads to damage from heat generation and high power levels of the motor. Variable speed motors are used with a feedback loop that keeps power at an acceptable level so as to avoid overheating. Alternatively the pump can be operated at full speed but use a by-pass valve between downstream and upstream sides, thereby preventing downstream pressure from being too high. In this way, gas compression generates less of the potentially dangerous heat. Once the downstream pressure becomes less than 20 Torr, the valve is no longer pushed open and the pump operates normally. Finally, manufacturer's can use a fluid drive to connect the pump to the rotors, so that the rotors do not get driven at motor speed due to slippage in the fluid drive caused by the viscosity of the fluid, which decreases once pressure has dropped sufficiently ("Pump Classification Technical Notes," 2007).

In order to pump out past the rough vacuum region, we have three pumps available in the laboratory, a turbo-molecular pump, an ion pump, and a cryogenic pump.

The turbo-molecular pump works by mounting blades in an alternating slotted arrangement (see Figures 6 and 7). As the gas molecules enter through the inlet valve, the first rotor impacts the gas molecule imparting downwards momentum (on average) that carries it to a downwards sloping stator (stationary component of the motor). The gas molecule slides down the stator and then collides with another rotor/stator pair. The many rotor/stator pairs allow relaxed clearance requirements on the moving parts, so that higher speeds (~16000 rpm) can be used. However, because of the higher speeds, significant frictional buildup makes it unwise to use such a pump at high pressures above 10^{-3} Torr. Moreover, because of the small mean free path of air at atmospheric pressure (~70nm), most pumps of this type cannot operate at atmosphere because the blades cannot be built with such a small clearance area. Normally, however, a backing pump is used. In a turbo-molecular pump, each rotor/stator pair typically has a compression ratio of around 10, so each stage closer to the outlet is considerably smaller than the prior one ("Turbomolecular pump," 2008). Since this pump is a compression pump, is limited by both out-gassing and back-leak. The ultimate pressure is equal to the effective back-leak conductance times the pressure of the fore-line (line between the fore-pump and vacuum pump), divided by the pump speed. Since pump speed and back-leak conductance are dependent on the mass of the gas molecules being pumped, it is more difficult to pump hydrogen or helium effectively (Berry, Hall, and Harris, 1968).

Figure 6: Alternating blade arrangement of a turbo-molecular pump acts to force impacted molecules downward.

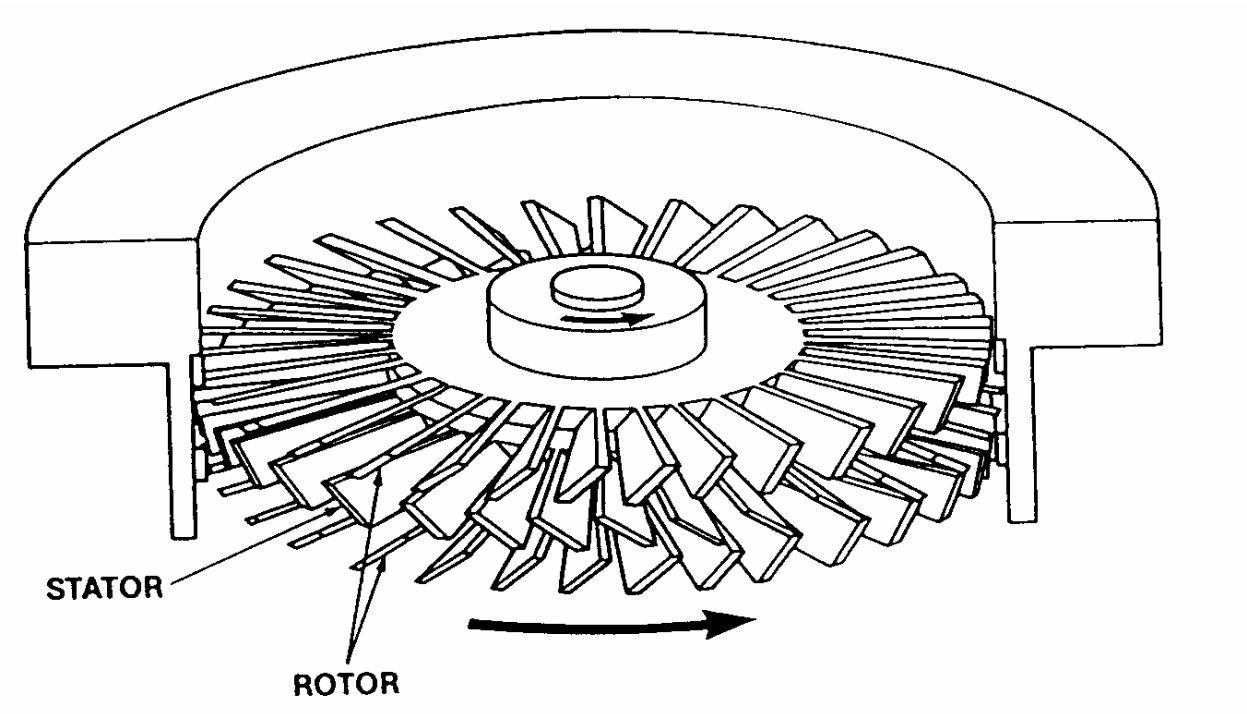


Figure 7: Turbo-molecular pump for pumping at high speeds of approximately 16000 rpm.

Turbo pumping speeds range from 50L/s to 3500L/s. Ultimate vacuum of most turbo-pums lies between 10^{-7} and 10^{-10} Torr. However, UHV is usually achieved by backing a large turbo by a small turbo, and then backing the small turbo by a mechanical pump. Turbo pumps are considered dry pumps because the lubricants are separated from the chamber and not used to seal. Lubricants used in the bearings or gears of the pump are prevented from traveling backwards due to the pumping mechanism ("Pump Classification Technical Notes," 2007).

The ion pump can also operate in the high vacuum region. Ion pumps have the advantage of being clean, heatable, and vibration free, while having long operating lives and low power consumption. All ion pumps use a parallel array of short, stainless steel tubes, two plates of either Ti or Ta that are spaced slightly away from the tubes, and a strong magnetic field parallel to the tube's axis. Pumping occurs from getter reactions and ion or neutral burial within the plates.

In the ion pump an electric field is generated that produces ions by electron collision. One possible method of doing this is with a diode pump. It uses an open anode lattice that accelerates electrons back and forth across the inside of the pump. Trajectories can be increased through the use of a magnetic field to force the electrons to spiral within the anode region (see Figures 8 and 9). The cathodes are covered with a chemically active "getter" material such as titanium, which will adsorb gas molecules. The electric field accelerates the ions to the cathode, where the getter material adsorbs the ions as a consequence of surface energy. Also, some getter materials may be reactive in order to increase pumping rates. However, inert gases are mostly pumped by adsorption to the cathode or ion burial within its lattice. The collision of the ion with the cathode wall results in some cathode material being sputtered unto the anode where it forms a

fresh gettering surface. This continually refreshed gettering surface is responsible for most of the pumping of active gases.

Figure 8: The components of an ion pump consist of a cathode that is covered with chemically active getter material, as well as magnets. Magnetic field acts to increase trajectory length to create more ions.

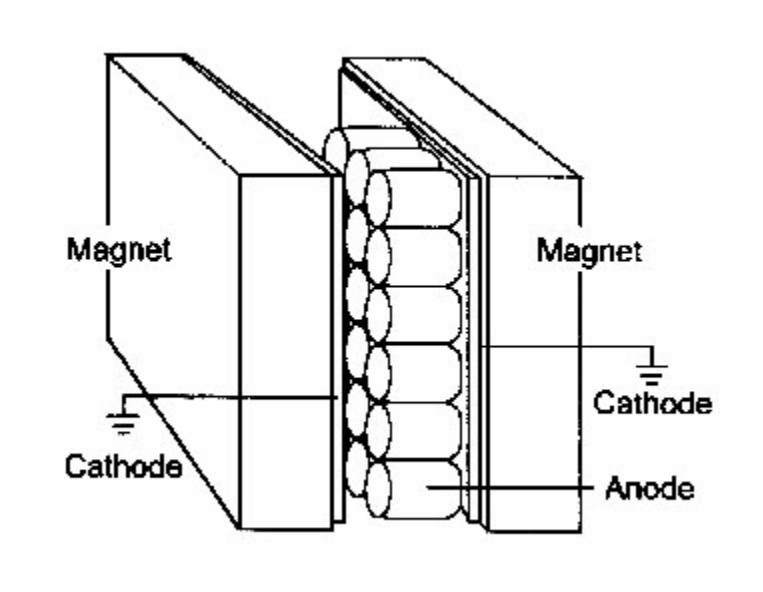
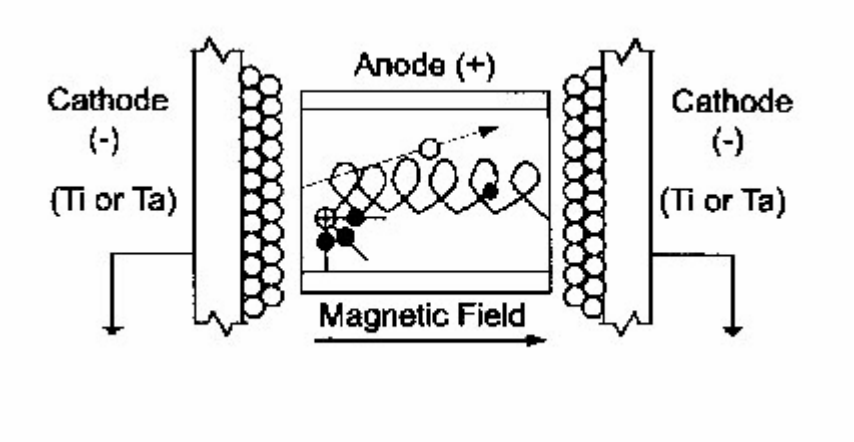


Figure 9: Ion pump in action below. The electrons from the cathode are repelled away through the anode region where they create ions that are attracted to and eventually embedded in the cathode's getter material.



Noble diode pumps replace one of the Ti plates with Ta, which reduces the pump's H_2 pumping speed while allowing for better pumping of noble gases. Electrons from the cathode plates move along helical trajectories in the magnetic field through the anodic tubes.

Finally, in a triode pump design the plates are hooked up to a negative voltage and are slotted so that new ions are accelerated into them. The slotted design increases the amount of deposition on the pump casing, which are less susceptible to releasing gas later due to ion bombardment.

The disadvantages of ion pumps include potential out-gassing due to temperature increases from starting the ion pump, finite lifetime before cathode replacement, and poor pumping of inert gases. This last condition is due to the inert gases being released from the cathode lattice structure when cathode material is sputtered off by fresh ions, thereby limiting efficiency ("Pump Classification Technical Notes," 2007).

The last pump we are using within the system is a cryogenic pump. A cryogenic pump operates by condensing gases onto a cold surface. The cryopump used on the system I was working on was cooled using liquid helium pumped by a cryo-compressor to the cold head. Cryopumps operate using a series of arrays for catching different gas molecules (as seen in Figure 10). The first stage of the array typically catches is around 80 K and catches water molecules. The next stage of the array is shaped like an inverted cup and is cooled to approximately 15 K; it is then able to condense atmospheric gases, as well as Ar that has been pumped into the system. Finally, lower sections of the pump are coated with an activated carbon sieve (as shown in Figure 11), a material with over 500 square meters of surface area per gram of material. This serves to bind materials using the Van der Waals force ("Activated carbon,"

2008). Because the material is granulated, most of the surface area is internal, so that gases which diffuse inside condense and become trapped in the material. This portion is extremely useful for pumping hydrogen and neon. Cryopumps are useful for pumping in the 10^{-6} to 10^{-9} Torr range. Disadvantages include poor helium pumping and vibrations caused by the cryo-compressor.

Figure 10: Cryogenic pump and its arrays. Each array functions to capture different types of molecules.

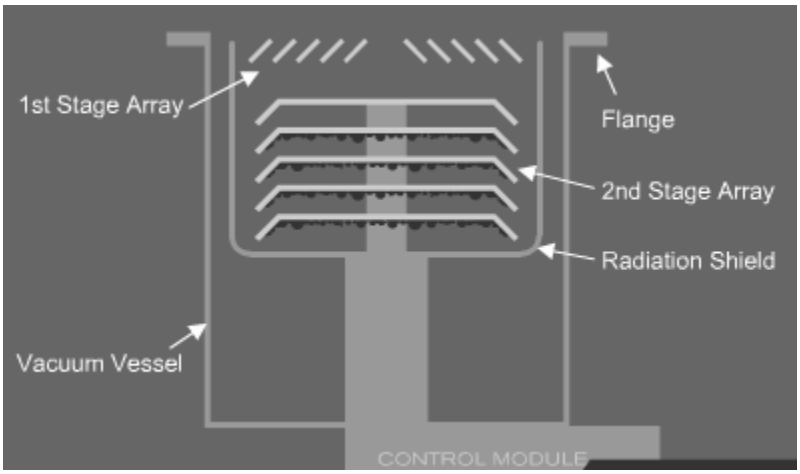
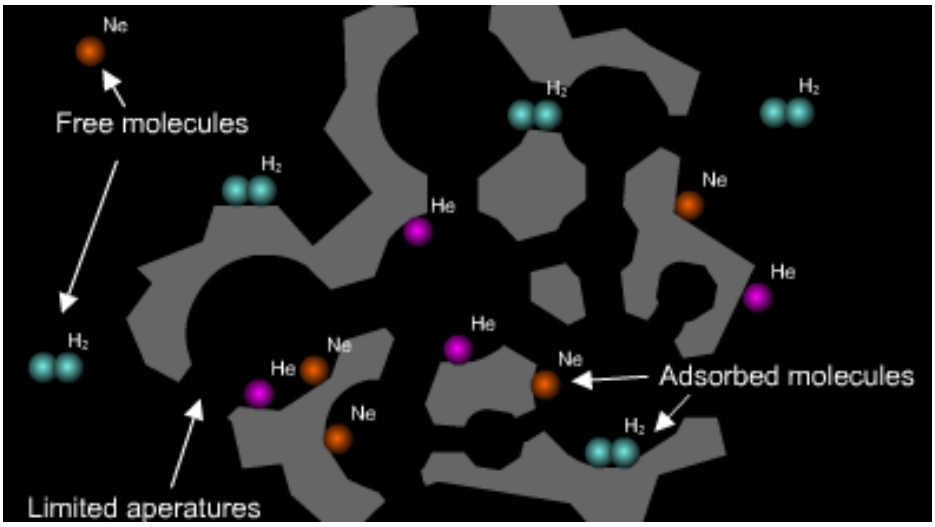


Figure 11: Activated carbon sieve attached to the second stage array for use in capturing hydrogen, helium, and neon.



Cryogenic pumps suffer little problem when used in the wrong vacuum range other than warming of the cold head from attempting to condense too many molecules, which causes the pumping mechanism to be ineffective. Moreover, there is a down time in which it is necessary to flush the cryo-pump heads after use. Because of the danger of polar water molecules getting trapped inside the molecular sieve pellets, nitrogen gas is often used to flush the system. Since gas molecules cannot diffuse against the stream of vapor, the danger is averted. Cryopumps are often used in semiconductor processes in which oil-free operation and high pumping speeds are necessary ("Pump Classification Technical Notes," 2007).

These various pumps are used together to pump down into the ultra-high vacuum range. However, it is useful to make sure that there are no leaks in the system; otherwise, the pumps may be unable to reach their maximum capabilities. Leaks are detected by injecting helium into potential leak sites and then attempting to detect the helium using mass spectrometry. Mass spectrometry is a technique for measuring the amount and composition of molecules in a system by use of their unique mass-to-charge ratio. The ions are created using an electrical filament. Various types of mass spectrometers exist for measuring these ions. For example, sector field mass analyzers that use an electric or magnetic field to deflect the ion path in order to detect different size ions by the current they produce in a faraday cup. In contrast, the quadrupole mass analyzer functions by using oscillating electric fields as shown in Figure 12. These electric fields confine the ions within the four rods shown in Figure 13. The quadrupole mass analyzer functions as a mass filter by changing the frequency of the oscillating electric fields. In this way, only the particular ion of the mass range being scanned is transmitted to the ion receptor. This reading gives the current, and through that, the partial pressure of a particular gas ("Mass Spectrometry," 2008).

Figure 12: Quadrapole, which isused to confine charged particles.

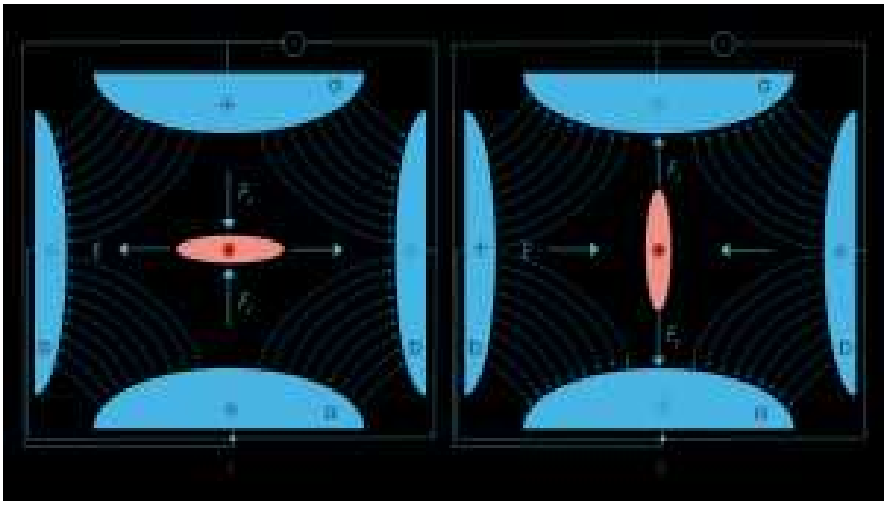
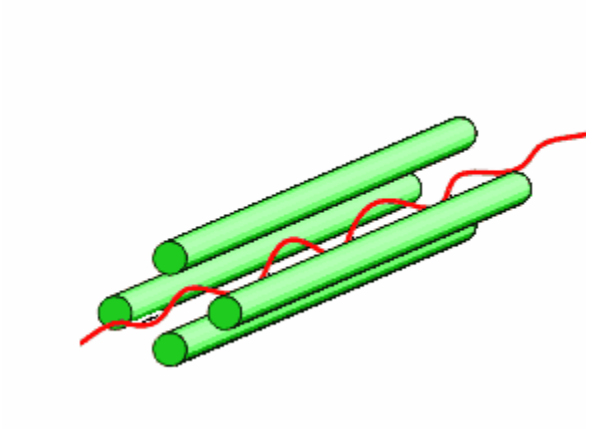


Figure 13: Quadropole mass analyzer functions by only allowing particles of a particular mass charge ratio to make it through the system without colliding.



Bake-out

Because metals tend to absorb or adsorb gas molecules into their structure, the system must be baked out in order to remove excess molecules, particularly water molecules from the system. Moreover, the mass spectrometer can be used to check water levels within the system to see whether a bake-out might be necessary. By heating the chamber, the process of out-gassing is accelerated, and pumps can then be used to reach higher levels of vacuum. In order to bake out

the system, the system must be enclosed and insulated to allow even heating. We used aluminum foil to create even heating and then attached heating tapes in order to heat the system to ~100 degrees Celsius. Baking takes a few days to complete, but it allows for much quicker pumping than allowing the material to outgas slowly and be pumped at natural rates ("Baking out the System," 2008).

Seals and Valves

In order to create and maintain a vacuum a system, it is necessary to have a method of connecting various parts of the system. In order to do this, there are a variety of connectors available, which are attached using flanges. Flanges act as semi-permanent connections to ports that can be used for a variety of instrumentation or closed so as to preserve the vacuum. In order for a flange to prevent leakage, they typically have a soft gasket of some kind squeezed between the harder stainless steel surfaces. The various gasket designs include rubber O-rings, elastomers, soft polymers covering a springy metal (UV), and soft metals (UHV). In our system, we used conflat (CF) type flanges which were sealed using copper gaskets. The copper gaskets are sealed by the CF flange using a knife-edge mechanism that activates as the bolts are tightened. The cut metal fills all the machining marks and inconsistencies in the surface to create a leak-tight seal.

Metal gaskets are impermeable to gases and withstand moderately high temperatures. However, the main reason that we used copper gaskets instead of rubber O-rings is that copper gaskets do not outgas as rubber seals. If rubber or elastomeric O-rings were used, the partial pressure from material out-gassing would limit the ultimate pressure of the vacuum system. Moreover, permeability increases as the temperature increases, making them poor choices for a system that may need to be baked out (Flanges, Fittings, and Components: Technical Notes," 2007).

An assortment of different valves exist for closing off vacuum volumes from the pumps and enabling transfer of samples from the loading chamber to the main sputtering chamber. Valves are also necessary to prevent sputtering onto the glass view ports. Valves consist of an actuator that transfers linear or rotary motion from the outside into the power needed to move the component sealing the valve, also known as a flapper. The flapper is typically made out of similar materials as the seals used on gaskets.

We also installed leak valves for the inlet of an inert process gas (argon) for sputtering or dry nitrogen gas to vent. Leak valves are highly sensitive to the flow rate, and are used to carefully insert gases up to a specified pressure.

Two common methods of controlling flow rate are needle valves and vacuum leak valves. A needle valve consists of a needle that fits into a conical sleeve, where slight movement of the needle adjusts the flow rate of the valve. Needle valves tend to be used when moderate to high flow rates from high pressure sources (above 1 bar) are needed. However, they have the disadvantage that when closed as much as possible, gas flow is still not cut off completely. Moreover, bake-out temperatures are limited to 200 degrees Celsius by the O-ring or Teflon seals. Because of this leak valves are typically used for ultra-high vacuum applications.

Leak valves can control extremely low flow rates using either a soft nickel pad surrounding a stellite (wear-resistant cobalt-chromium alloy) knife-edge ring or by using a copper gasket that is conformed to the surface of a soft, polished sapphire pad. Leak valves, when closed, shut off gas flow entirely, and because they use metal bellows for the actuator, bake-out up to ~450 degrees Celsius is possible (“Valves: Technical Notes,” 2007).

Traps and Filters

Traps are typically used to capture gases and vapors. Usually, traps are defined as working at best in the 10^{-3} Torr range, while filters operate above that. Traps are used as either fore-line traps (placed between the high-vacuum pump and the mechanical pump) or system traps. Fore-line traps are primarily used to capture back-streaming oil or chamber vapors, and are typically filled with some adsorbent material, cryogen, or fibrous wool. Molecular sieves are normally made of activated carbon, activated alumina, or zeolite (an alumino-silicate). Molecules become trapped in the micro-pores and channels of the material's large surface area. These materials must be regenerated by baking out and pumping. Nitrogen gas is again used to flush out water vapor during baking.

Another method of trapping is using metal wools, also known as conversion traps. Metal wools have smaller surface area than molecular sieves, but because they are not limited to covering the surface with mono-layers, they may have equivalent retention of oil vapor. However, they have the disadvantage of being more likely to release oil back upstream due to the wool only loosely binding molecules to its surface. Also, conversion traps have the disadvantage of needing their elements replaced regularly.

The final method is to use cryogenic materials to adsorb molecules in the same way that a cryogenic pump works. However, all these methods are not ideal for the hazards of pumping process vapors or corrosive vapors. Process vapors present gas loads large enough to overcome the small capacity of fore-line pumps, while corrosive vapors tend to cause damage to the pumps and require either large corrosion-resistant pumps or bulk cryogens.

There are also various system traps (traps for use near the chamber). For example, there are often traps based placed the chamber and the diffusion pump to prevent oil back-streaming. Usually liquid nitrogen traps and shrouds, baffles with water-cooled compressors, or meissner traps are used for system traps. Usually water-cooled baffles are not used in place of liquid nitrogen pumps but act as thermal barriers between the LN_2 system traps and other pumps. Meissner traps are basically coils filled with a cryogen to pump water vapor.

In contrast to traps that capture gases and vapors, filters capture particles, chemical smokes, and aerosols. There are two basic methods to filtering: either an element of some kind is used to entangle particles that fly into their fabric, or to use a centrifugal principle, moving particles in a circle with a pump until the particles fall to the ground under gravity (also known as a cyclone filter).

Fore-line filters are used to catch dust particles made in the vacuum process or that flake off the metal in the system. Another type of filtering that occurs in the system is mist elimination. This prevents oil aerosols created by the oil reservoir on a pump from exhausting into the atmosphere. These mist eliminators typically use a filter element to increase the energy required to escape, thereby forcing the mist to coalesce deposit back into the oil reservoir.

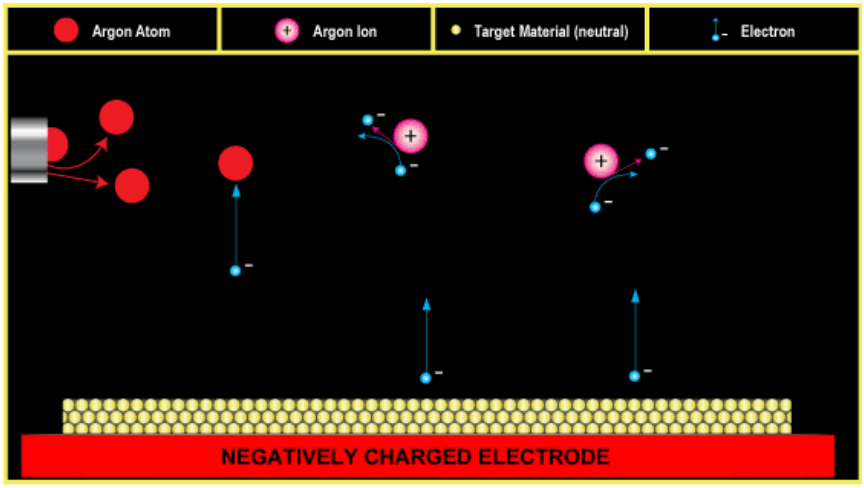
Finally, most rough pumps have a filter to prevent particles from mixing with the oil to create sludge. These typically trap particles that are greater in size than 0.2 microns. Oil pumps also tend to have process gases that are neutralized using activated aluminum (“Traps and Filters Technical Notes,” 2007).

Sputtering System

For my project, I assisted in the setup of the magnetron sputter deposition system in Professor Lukaszew's laboratory. This system consisted of the main sputtering chamber with ports for five guns, a substrate holder/heater, and various ports for additional instruments such as ion gauges, diagnostic tools, etc. The system also had a transfer arm and load-lock chamber, so that a number of substrates could be brought into the main chamber without needing to open it to atmosphere. When tightened, a knife edge of a flange cuts the copper gaskets so as to have a razor edge connection. I helped connect the transfer arm to the main sputtering chamber, and aided in the installation of the magnetron guns and other equipment.

Sputter deposition utilizes atomic removal from the target's surface, which are then projected onto the surface. The old method of sputtering consisted of setting up a dynamic inert plasma (argon in our case) and using it as a source for Argon ions. A target cathode and a substrate anode are mounted a few inches apart. The inert process gas flows between the electrodes, and electrons from the target's surface initiate an ionization cascade to form plasma (Figure 14).

Figure 14: Creation of argon plasma from surface electrons.



Because the plasma is electrically neutral and highly conductive, there is little voltage drop across it. Instead, the voltage drop occurs across dark spaces between the plasma and the electrodes. Positive ions are therefore discharged into the negatively charged cathode. These positive ions hit with sufficient power to knock free neutral target atoms or molecules by kinetic energy transfer. These then fly along line of sight and deposit on the substrate (Figure 15). Finally, free electrons recombine with the argon ions, neutralizing them and releasing photons (see Figure 16). These photons are responsible for the slightly pink plasma discharge visible during the sputtering process.

Figure 15: Sputtering of target material and deposition on substrate.

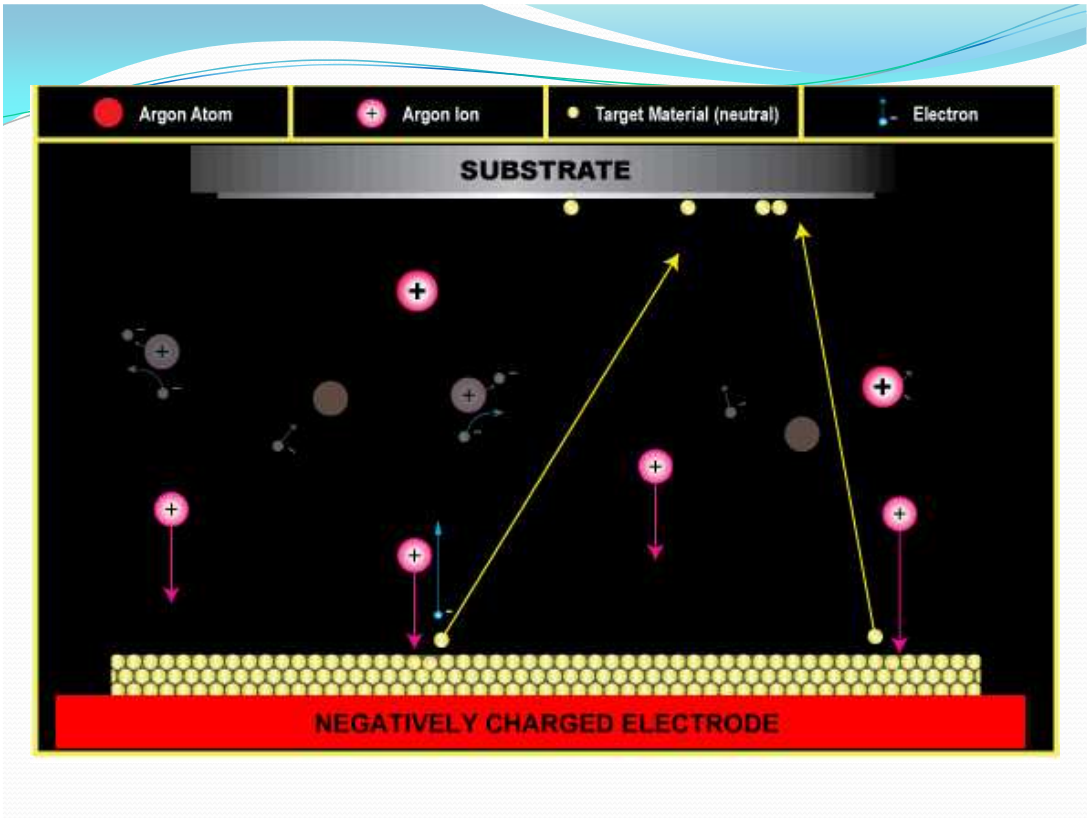
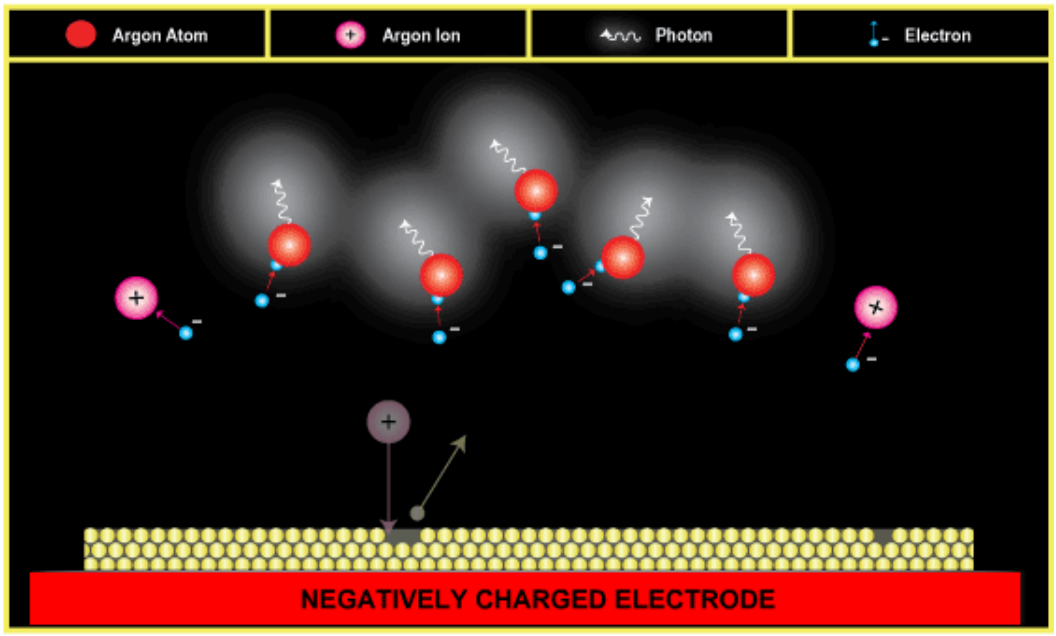


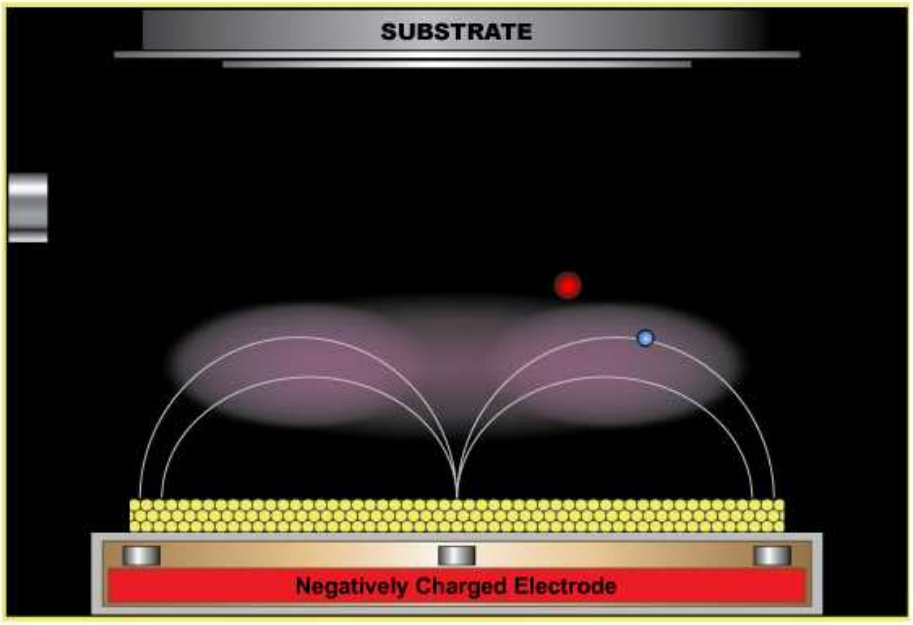
Figure 16: Neutralization of argon atoms and release of photons.



It is important that the mean free path be large enough that atoms are not completely scattered and fail to reach the target. However, it is also important to optimize the distance between the target and substrate so as to produce a uniform film. Since we use circular sources, this means making sure the distance is greater than the target's diameter so as to smooth out the ring like concentration gradient.

Diode sputtering used contoured targets to shape the plasma with the electric field. However, this has been replaced with magnetron sputtering. In magnetron sputtering, magnets in the magnetron gun enhance the curved path of the ions in the plasma towards the target and thus enhance the sputter yield that deposits on the substrate (Figure 17). The magnetic field also has the added benefit of preventing unnecessary heating and possible structural damage to the substrate, as normally free electrons would extensively bombard the positively-charged substrate.

Figure 17: Magnetic field containing electrons near the surface of the target.



The magnetron guns we are using use indirect cooling in which water cools the non-vacuum side of the cooling well for the magnetron guns. Since the targets are not bonded to their cooling wells, poor heat transfer (particularly with low thermal conductivity targets) can lead to thermal expansion stress cracks in the target or melting of the indium bonding (which is melted to the target). One alternative is to apply a glue paste instead of using indium to bond. Thermally conductive polymer sheets and silver-impregnated paste are often used to improve thermal contact, while the power supply is usually ramped up and stopped periodically to allow the temperature to adjust gradually and prevent stresses from forming cracks.

Another crucial part of enhancing the sputter yield is to use a power supply suited for the target. Electrically conducting metal, alloy, and compound targets cause no ion charging issues and are sputter with DC power. Sputtering a material with poor electrical conductivity using DC power leads to charge build-up. Energetic ions are buried in the target's surface but its resistivity prevents neutralization by electrons from adjacent electrodes. The target charge acts as an

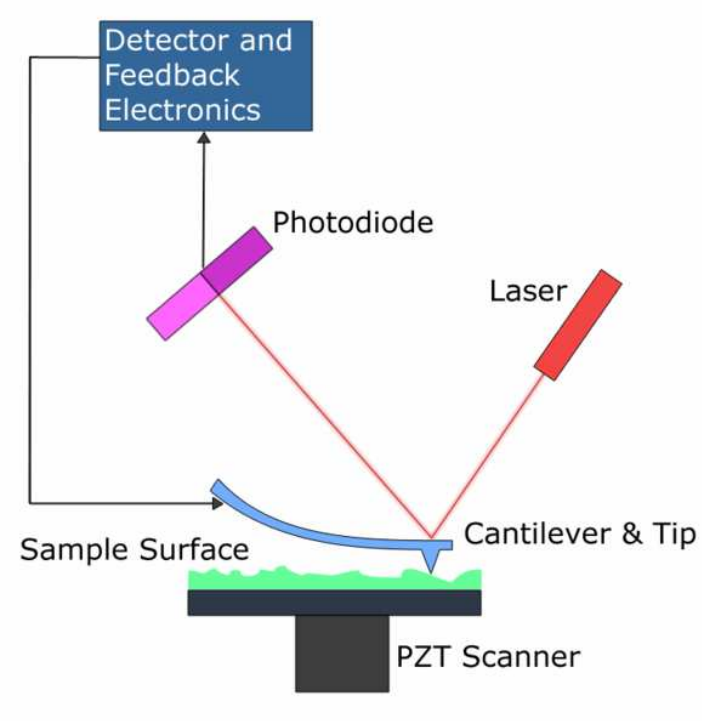
electrical barrier preventing further ion bombardment. Poor electrical conductors are sputtered using RF or pulsed DC power. The RF's reversal of electrode polarity or the negative surface bias present during the pulsed DC's 'off' period, causes the highly mobile electrons from the plasma to quickly flood and neutralize the surface.

Characterization techniques

In order to characterize the films we plan to use various *in situ* and *ex situ* methods. Inside the vacuum system, we will use RHEED (Reflection high-energy electron diffraction) techniques to analyze the structure of crystalline materials. RHEED systems gather information about the surface of the sample as it grows, which is apt for thin film studies. A RHEED system consists of an electron source that is fired at a glancing angle at the sample's surface, which then projects a diffraction pattern onto a photo-luminescent screen("Reflection high energy electron diffraction," 2008).

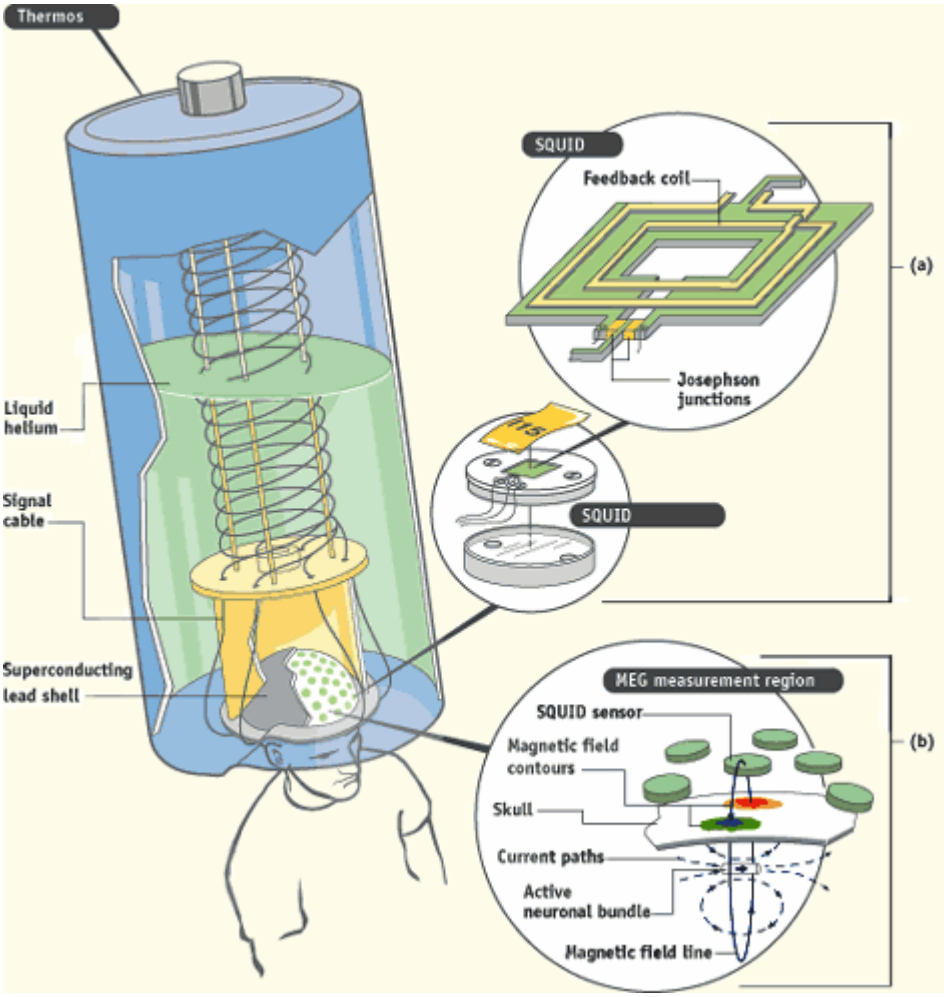
Another method of characterization we intend to use to analyze samples is atomic force microscopy. AFM techniques are capable of measuring resolutions in the fractions of a nanometer by measuring the deflection of an extremely fine needle tip by the microscopic forces of the sample (see Figure 18). Typically, the deflection is measured with a laser reflected from the cantilever into photodiodes that record the slight movement. This is then tied into a feedback mechanism to prevent the delicate tip from brushing the surface and becoming damaged ("Atomic force microscope," 2008).

Figure 18: Atomic force microscope operates by deflection of a needle tip by atomic forces. Electrons then measure the deflection of the tip to create an image.



For the purposes of measuring the magnetic properties of media, we will make use of a SQUID (superconducting quantum interference device). SQUIDs measure extremely small magnetic fields by using super-conducting loops known as Josephson junctions ("SQUID," 2008). These junctions consist of two superconductor elements weakly coupled together by an insulator. The current that crosses this junction as the sample moves through the SQUID allows one to calculate the direction and strength of the magnetic field ("Josephson effect," 2008). In order to analyze the magnetic effects of nanostructures, such delicate instrumentation is a necessary tool.

Figure 19: The SQUID measures tiny magnetic fields using super-conducting loops that measure the induced current from the magnetic fields.



Conclusion

Compared with other thin film deposition techniques (thermal and e-beam evaporation), magnetron sputtering has numerous advantages. The high kinetic energy of sputtered atoms gives better film adhesion, and randomized deposition results in improved step coverage. For industrial applications, sputtering can be made into a continuous, inline process. Although the plasma is energetically 'hot', it has a low thermal capacity and does not heat the substrate. Especially, sputtering can deposit films of refractory materials, elements, mixtures, and alloys with facile accommodation, which can then be analyzed to observe changes in the properties of the material.

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